# Biomechanical Determinants of the Jumper's Knee in Volleyball

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# RELATIONSHIP BETWEEN LANDING STRATEGY AND PATELLAR TENDINOPATHY

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**Abstract**

The aetiology of patellar tendinopathy (jumper's knee) remains unclear. To see whether landing strategy might be a risk factor for the development of this injury, this study examined whether landing dynamics from drop jumps differed among healthy volleyball players (CON) and volleyball players with a jumper's knee. The patients with jumper's knee were divided into an asymptomatic group with a previous jumper's knee (PJK) and a symptomatic group with a recent jumper's knee (RJK).

Inverse dynamics analyses were used to estimate lower extremity joint dynamics from 30, 50 and 70 cm drop jumps in the three groups (CON, $n = 8$; PJK, $n = 7$; RJK, $n = 9$). A univariate repeated measures analysis of variance was used to compare the different landing techniques.

Data analysis of the landing dynamics revealed that PJK showed higher knee angular velocities ($p<0.01$), and higher ankle plantar flexion moment loading rate ($p<0.01$). Furthermore, strong tendencies of higher loading rate of vertical ground reaction force ($p = 0.05$) and higher knee extensor moment loading rate ($p = 0.08$) were found compared with CON. Higher values for peak knee moment, peak knee power and knee work (all $p<0.01$) were found for CON compared with RJK. The comparison of the two jumper's knee groups yielded higher knee angular velocities ($p<0.01$), together with higher ankle plantar flexion and knee extensor moment loading rate ($p<0.01$ and $p<0.05$, respectively).

Where RJK used a landing technique to avoid high patellar tendon loading, PJK used a stiffer landing strategy, which may be a risk factor in the development of patellar tendinopathy.

**4.1. Introduction**

Patellar tendinopathy (jumper's knee) is the most common injury among volleyball players, with a prevalence between 40% and 50% among elite players (Lian et al., 2003; Lian et al., 2005). In many cases, this injury causes a reduction in playing level and a long interruption of training and competition. The high prevalence induces further research to focus on the underlying mechanism that plays a role in the aetiology of patellar tendinopathy, to develop suitable preventive strategies (Van Mechelen et al., 1992).

Patellar tendinopathy originates from repetitive loads exposed to the quadriceps extensor mechanism (eg, patellar tendon) during the jump–landing sequence. After cumulative microtrauma, degenerative changes of the tendon can take place (Cook et al., 2004).

Factors such as training volume and floor type were associated with the incidence of patellar tendinopathy (Ferretti et al., 1990). The latter was in line with a lower prevalence in elite beach volleyball players, who play on soft sandy undergrounds (Bahr & Reeser, 2005). Female elite athletes are twice less vulnerable to patellar tendinopathy than their male counterparts (Lian et al., 2005; Cook et al., 1998), which might be caused by the fact that women in general generate less power. Furthermore, the demonstration that patients with jumper's knee show better jumping ability and power generation than healthy players suggests that volleyball players with a jumper's knee subject their quadriceps extensor mechanism to higher loads (Lian et al., 2003).

An inverse dynamics analyses approach (Richards et al., 1996; Richards et al., 2002) was used to suggest several lower extremity dynamical variables during both take-off and landing phase of a volleyball jump, related to the presence of patellar tendinopathy. However, its relationship with the aetiology of patellar tendinopathy remains equivocal, because of the possible adaptation by symptomatic patients with jumper's knee on jump and landing dynamics due to pain.

During the jump–landing sequence in volleyball, the landing strategy is essential to accommodate the excessive impact forces efficiently, and is thought to be related to the athlete's risk for injuries (James et al., 2003; Reeser et al., 2006). Further landing studies revealed the effect of joint kinematics (Devita & Skelly, 1992), jump height (McNitt-Gray, 1993) and gender (Decker et al., 2003; Salci et al., 2004) on the quadriceps extensor mechanism. The importance of excessive impact forces exerted around the knee joint during landing and the potential role of landing strategy on the development of patellar tendinopathy have not fully been clarified so far.

Therefore, the aim of this study was to describe the biomechanics of the landing strategy of three groups: volleyball players with a recent symptomatic patellar tendinopathy, volleyball players with a history of patellar tendinopathy and volleyball players without patellar tendinopathy, to find indications of possible risk factors for patellar tendinopathy.

## 4.2. Methods

### Inclusion procedure: diagnosis of patellar tendinopathy

In March 2004, 89 male volleyball players from the northern part of The Netherlands completed a questionnaire measuring the type, history, prevalence and severity of knee injuries in volleyball. Depending on the questionnaires' outcomes, people were invited to participate in this study. Measurements took place in September 2004, which was the beginning of the volleyball season. Beforehand, participants signed the written informed consent, approved by the local ethics committee. After a clinical examination by an experienced sports physician, participants were divided into three different groups based on the following diagnostic criteria:

Group 1 was the control group (CON) with no history of patellar tendon pain, no pain during a single leg decline squat (Cook et al., 2000) and no palpation tenderness (Cook et al., 2001). The athletes also recorded pain, function and athletic activity using the Victorian Institute of Sport Assessment (VISA) Scale (Visentini et al., 1998) of ≥80 points.

Group 2 was the asymptomatic group with a previous jumper's knee (PJK). Inclusion criteria for this group were a history of pain localised to the proximal patellar tendon or insertion of the quadriceps tendon, patellar tenderness, but no pain during single decline squat and a VISA score >80 points. Furthermore, this group reported no symptoms in the patellar tendon or its insertion over the past 5 months. The players were free of symptoms for up to 12 months.

Group 3 was the symptomatic group with a recent jumper's knee (RJK), with the following inclusion criteria: pain during single leg decline squat, palpation tenderness and a VISA score <80 points.

Exclusion criteria were a history of recent injury at the lower extremities or the back for the past 3 months (besides RJK concerning the patellar tendon region) or any surgery in the lower extremities and the back. In case of bilateral patellar tendinopathy, the more symptomatic knee was selected for the study. To verify the group division based on the diagnostic procedure, players were asked to report pain in the patellar tendon region on a scale of 1–5 (1, no pain; 5, intense pain) during measurements.

### Participants

Table 4.1 presents the participants' characteristics. All athletes participated in volleyball at least three times a week and had been competitive for at least 5 years. During the measurements participants wore their own indoor sport shoes.

### Procedures

Before measurements, participants followed a warming-up and stretching routine. Drop jumps were performed from 30, 50 and 70 cm high platforms, situated behind a force plate. The landing task consisted of stepping off the platform to land as naturally as possible with both feet on the ground (one foot on the force plate), while looking forward. Measurements were carried out for the right and left leg separately, and were started at 50 cm, followed by 30 and 70 cm (series of five each). Video registration of the landings was used to verify adequate landing.

Table 4.1. Mean (SD) values for the participants' characteristics for control, previous jumper's knee and recent jumper's knee groups.

| | **CON** n=8 | **PJK** n=7 | **RJK** n=9 |
|---|---|---|---|
| age | 23.6 | 22.4 | 24.1 |
| | -2.5 | -2.6 | -3.3 |
| body mass (kg) | 84.5 | 79.5 | 85 |
| | -13.2 | -5.6 | -10.1 |
| height (m) | 1.89 | 1.89 | 1.92 |
| | -0.08 | -0.07 | -0.06 |
| leg length (m) | 1.01 | 1.03 | 1.05 |
| | -0.05 | -0.06 | -0.04 |
| VISA score | 97.8 | 94.8 | 70.2 |
| | -3.7 | -5.1 | -7.9 |
| **field position** | | | |
| setter | n=3 | n=1 | n=1 |
| blocker | n=1 | n=3 | n=3 |
| spiker | n=4 | n=3 | n=5 |
| **playing level** | | | |
| elite division | n=1 | n=1 | n=2 |
| first division | n=3 | - | - |
| second division | n=1 | n=3 | n=1 |
| third division | n=3 | n=3 | n=6 |

### Instrumentation

To record the landing movement, position data were collected at 200 Hz using an Optotrak motion analysis system with two cameras containing three sensors each. Three moulded rigid frames (3.2 mm Aquaplastic), each containing four light-emitting markers, were tightly attached to the pelvis, thigh and shank with wide neoprene bandages and Velcro fasteners. Four foot-segment markers were attached to the shoe at the lateral side of the calcaneus. A Bertec force plate (type 4060–08) was used to measure the three components of the ground reaction force, and the three components of the external moment at a sampling rate of 1000 Hz. The position of the centre of pressure was computed afterwards. After amplifying, all force plate signals were converted to digital signals by the 16 bit A/D converter of the Optotrak system.

### Data analysis

The obtained position data were filtered through a second-order low-pass zero-phase Butterworth filter with a cut-off frequency of 20 Hz. From these filtered marker trajectories, joint angles were calculated (Grood & Suntay, 1983), where hip flexion, knee extension and ankle dorsal flexion were positive.

Force plate data were smoothed using the same filter, with a cut-off frequency of 100 Hz. Loading rate vertical ground reaction force (LR VGRF) was defined as the peak VGRF value divided by time from touch down to peak value. A Matlab V.6.5-based motion analyses program BodyMech (Free University, Amsterdam) processed both kinematic and force plate data. Using a four-segment rigid-body model, together with anthropometric data (de Leva, 1996), inverse dynamics assessed ankle, knee and hip joint dynamics. For the assessment of joint moments, the force plate data were filtered with a cut-off frequency of 20 Hz to minimise impact peak errors in the moment calculation caused by the impact peak of the ground reaction force (Bisseling & Hof, 2006). The calculation of joint moments was based on the equations of motion as formulated by Hof (1992). The rate of force development generated by the structures around the ankle and knee joint was reflected by the loading rate of ankle and knee joint moment. These loading rates were defined as the peak value of the first derivative of the moment curve. Joint moments were presented in local joint coordinate systems, according to Grood and Suntay (1983) and Wu et al. (2002) Joint work was calculated by integration of the joint power, starting at touch down and ending at the end of the negative phase. To reduce inter-subject variability, biomechanical variables were presented as dimensionless measures, normalised and expressed according to Hof (1996).

**Statistical analysis**

After checking every landing trial with digital video data for incorrect performance of the drop jump landing (jumping up or stepping down from the platform, or move too much forward immediately after impact), statistical means (SD) were calculated from all trials for each subject.

SPSS V.11.5 was used to analyse the data. Pearson's correlation was used to assess the relationship between the degree of knee flexion at the time of peak VGRF and VGRF parameters: peak VGRF and LR VGRF. A univariate repeated measures analysis of variance was used to compare the mean biomechanical outcomes of the right and left leg trials of CON with the symptomatic leg trials of PJK and RJK. Main effects between groups were calculated after we checked whether sphericity assumptions were violated. If this was the case, the Greenhouse–Geisser correction of degrees of freedom was applied. Factor drop jump height was the repeated measure and group (CON, PJK and RJK) was the between-subject variable. Tukey HSD post hoc analysis was used to determine the group differences ($p<0.05$).

The dependent biomechanical variables were peak VGRF, LR VGRF, joint flexion angles, joint angular velocity, joint peak moments, loading rates of ankle and knee moments, and joint power and work.

## 4.3. Results

There was a significant main effect for drop jump height across all groups for all biomechanical parameters except for the kinematic variables ankle, knee and hip flexion angles at the time of peak VGRF (Tables 4.2 and 4.3).

Table 4.4 presents the data that reflect the influence of the degree of knee flexion on external load. Knee flexion angle at the time of peak VGRF was negatively correlated with peak VGRF as well as with LR VGRF among all three groups and heights, except for the RJK group at 70 cm.

Table 4.2. Mean (SD) values of ground reaction force and joint kinematics for control, previous jumper's knee and recent jumper's knee groups for 30, 50 and 70 cm drop jump.

| | CON | | | PJK | | | RJK | | |
|---|---|---|---|---|---|---|---|---|---|
| | 30 cm | 50 cm | 70 cm | 30 cm | 50 cm | 70 cm | 30 cm | 50 cm | 70 cm |
| **VGRF** | 2.226 | 2.819 | 3.070 | 2.775 | 3.421 | 3.795 | 2.162 | 2.939 | 3.148 |
| | (0.653) | (0.882) | (0.876) | (0.559) | (0.569) | (0.803) | (0.778) | (1.123) | (1.206) |
| **LR VGRF** | 13.834 | 19.187 | 20.609 | 22.682 | 28.245 | 30.871 | 13.584 | 19.730 | 27.369 |
| | (6.902) | (9.543) | (9.340) | (8.391) | (7.634) | (9.724) | (8.144) | (9.901) | (12.602) |
| **Ankle kinematics** | | | | | | | | | |
| flexion td (deg) | -32.387 | -36.437 | -37.942 | -30.626 | -34.346 | -35.289 | **-33.044** | **-40.228** | **-40.638** |
| | (4.244) | (4.672) | (3.646) | (9.139) | (5.225) | (5.109) | **(5.864)** | **(5.545)** | **(5.677)** |
| flexion (deg) | 6.716 | 7.983 | 9.695 | 3.215 | 4.313 | 6.172 | 1.578 | 2.143 | -5.307 |
| | (5.623) | (4.046) | (4.003) | (4.818) | (3.868) | (5.209) | (5.765) | (5.347) | (15.608) |
| ROM (deg) | 48.687 | 55.863 | 57.390 | 48.775 | 55.514 | 57.227 | 47.458 | 53.294 | 55.871 |
| | (5.853) | (6.404) | (4.784) | (5.466) | (5.120) | (7.304) | (5.466) | (5.120) | (4.766) |
| angular velocity | 5.498 | 6.895 | 7.486 | 5.925 | 7.246 | 7.721 | 5.416 | 6.747 | 7.575 |
| | (0.649) | (0.874) | (0.922) | (0.661) | (0.531) | (0.940) | (0.854) | (0.992) | (0.7770 |
| **Knee kinematics** | | | | | | | | | |
| flexion td (deg) | -18.303 | -19.434 | -23.762 | -15.692 | -16.813 | -21.366 | -19.231 | -18.897 | -21.617 |
| | (6.665) | (5.856) | (4.887) | (6.284) | (4.208) | (6.254) | (6.999) | (7.484) | (6.519) |
| flexion (deg) | -46.420 | -48.063 | -52.700 | -36.077 | -38.527 | -44.230 | -44.337 | -43.282 | -40.349 |
| | (13.576) | (10.521) | (9.540) | (7.568) | (6.283) | (9.352) | (16.814) | (15.181) | (9.188) |
| ROM (deg) | 56.756 | 67.667 | 75.233 | 57.640 | 67.490 | 76.238 | 55.354 | 62.361 | 70.643 |
| | (11.215) | (11.194) | (11.097) | (7.681) | (7.529) | (8.798) | (17.578) | (17.313) | (17.708) |
| angular velocity | -3.404 | -3.967 | -4.030 | *-4.119* | *-4.600* | *-4.575* | *-3.121* | *-3.609* | *-3.996* |
| | (0.319) | (0.379) | (0.254) | *(0.507)* | *(0.627)* | *(0.714)* | *(0.412)* | *(0.465)* | *(0.387)* |
| **Hip kinematics** | | | | | | | | | |
| flexion td (deg) | 21.547 | 22.289 | 25.442 | 15.491 | 15.749 | 18.339 | 19.323 | 20.059 | 19.055 |
| | (6.484) | (7.426) | (6.540) | (6.811) | (5.487) | (7.937) | (10.026) | (10.643) | (8.925) |
| flexion (deg) | 30.823 | 31.664 | 35.530 | 21.667 | 23.625 | 26.877 | 30.649 | 31.300 | 28.931 |
| | (10.374) | (10.321) | (9.337) | (8.493) | (7.175) | (10.016) | (14.437) | (13.266) | (9.368) |
| ROM (deg) | 22.278 | 33.616 | 40.857 | 24.615 | 35.066 | 44.583 | 25.595 | 32.674 | 40.229 |
| | (8.781) | (12.409) | (10.779) | (10.265) | (10.725) | (11.869) | (16.261) | (18.487) | (17.418) |
| angular velocity | 1.618 | 2.158 | 2.690 | 2.045 | 2.482 | 2.764 | 1.822 | 2.182 | 2.487 |
| | (0.368) | (0.414) | (1.039) | (0.618) | (0.605) | (0.488) | (0.554) | (0.556) | (0.857) |

CON, control; deg, degrees; Flexion td, joint flexion at the time of touch down; Flexion, flexion angle at the time of peak VGRF; LR VGRF, loading rate vertical ground reaction force; PJK, previous jumper's knee; RJK, recent jumper's knee; ROM, range of motion.

Bold font, significant difference compared with CON; italic font, significant difference between PJK and RJK.

VGRF is scaled to m•g (product of body mass and gravity). LR VGRF is scaled to $m \cdot g^{1½} \cdot l_0^{-½}$ (body mass times gravity to the power 1½ divided by the square root of leg length). Angular velocity is scaled from $rad \cdot sec^{-1}$ to $(g/l_0)^{½}$.

Table 4.3. Mean (SD) values of the joint kinetics and energetics for control, previous jumper's knee and recent jumper's knee for 30, 50 and 70 cm drop jump.

| | **CON** | | | **PJK** | | | **RJK** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **30 cm** | **50 cm** | **70 cm** | **30 cm** | **50 cm** | **70 cm** | **30 cm** | **50 cm** | **70 cm** |
| **Peak joint moment** | | | | | | | | | |
| ankle (Ma) | -0.171 | -0.205 | -0.227 | -0.165 | -0.201 | -0.219 | -0.147 | -0.188 | -0.196 |
| | (0.026) | (0.035) | (0.032) | (0.027) | (0.024) | (0.032) | (0.035) | (0.041) | (0.035) |
| knee (Mk) | 0.212 | 0.231 | 0.255 | 0.194 | 0.216 | 0.231 | **0.154** | **0.175** | **0.208** |
| | (0.035) | (0.033) | (0.034) | (0.019) | (0.020) | (0.030) | **(0.048)** | **(0.051)** | **(0.047)** |
| hip (Mh) | -0.115 | -0.163 | -0.189 | -0.152 | -0.187 | -0.239 | -0.141 | -0.180 | -0.185 |
| | (0.036) | (0.056) | (0.048) | (0.027) | (0.027) | (0.060) | (0.053) | (0.060) | (0.067) |
| LR Ma | -1.619 | -2.126 | -2.305 | ***-2.155*** | ***-2.955*** | ***-3.120*** | *-1.459* | *-2.046* | *-2.318* |
| | (0.559) | (0.596) | (0.485) | ***(0.559)*** | ***(0.679)*** | ***(0.835)*** | *(0.568)* | *(0.791)* | *(0.734)* |
| LR Mk | 2.301 | 3.156 | 3.299 | *3.062* | *3.850* | *4.425* | *2.232* | *2.736* | *3.069* |
| | (0.717) | (0.890) | (0.842) | *(0.897)* | *(1.163)* | *(1.596)* | *(0.640)* | *(0.760)* | *(0.993)* |
| **Peak joint power** | | | | | | | | | |
| ankle (Pa) | -0.649 | -1.101 | -1.191 | -0.756 | -1.199 | -1.373 | -0.660 | -0.984 | -1.098 |
| | (0.186) | (0.282) | (0.261) | (0.182) | (0.136) | (0.335) | (0.258) | (0.395) | (0.343) |
| knee (Pk) | -0.573 | -0.756 | -0.855 | *-0.616* | *-0.846* | *-0.962* | *-0.392* | *-0.537* | *-0.690* |
| | (0.151) | (0.157) | (0.156) | *(0.111)* | *(0.129)* | *(0.136)* | *(0.119)* | *(0.147)* | *(0.203)* |
| hip (Ph) | -0.118 | -0.200 | -0.287 | -0.188 | -0.287 | -0.359 | -0.128 | -0.224 | -0.281 |
| | (0.029) | (0.072) | (0.107) | (0.060) | (0.073) | (0.104) | (0.051) | (0.108) | (0.149) |
| **Joint work** | | | | | | | | | |
| ankle (Wa) | -0.089 | -0.118 | -0.132 | -0.086 | -0.117 | -0.129 | -0.083 | -0.105 | -0.126 |
| | (0.015) | (0.023) | (0.015) | (0.027) | (0.023) | (0.036) | (0.027) | (0.023) | (0.024) |
| knee (Wk) | -0.119 | -0.174 | -0.224 | -0.109 | -0.154 | -0.203 | **-0.091** | **-0.112** | **-0.141** |
| | (0.033) | (0.038) | (0.054) | (0.016) | (0.017) | (0.032) | **(0.040)** | **(0.048)** | **(0.064)** |
| hip (Wh) | -0.018 | -0.036 | -0.064 | -0.025 | -0.038 | -0.059 | -0.023 | -0.046 | -0.049 |
| | (0.009) | (0.021) | (0.038) | (0.017) | (0.020) | (0.030) | (0.014) | (0.028) | (0.022) |

CON, control; PJK, previous jumper's knee; RJK, recent jumper's knee. Bold font, significant difference compared with CON; italic font, significant difference between PJK and RJK. Peak joint moments are scaled to $m \cdot g \cdot l_0$ (product of body mass, gravity and leg length).
Peak joint powers are scaled to $m \cdot g^{1½} \cdot l_0^{½}$ (body mass times gravity to the power of 1½ times square root of leg length)
Loading rate (LR) of joint moments are scaled to $m \cdot g^{1½} \cdot l_0^{½}$.

Table 4.4. Pearson's correlation coefficients between knee flexion angles at the time of peak vertical ground reaction force (VGRF) and peak VGRF and loading rate (LR) VGRF.

| | DJ height | Knee flexion angle peak VGRF | Knee flexion angle LR VGRF |
|---|---|---|---|
| **CON** | 30 cm | -0.78** | -0.82** |
| | 50 cm | -0.90** | -0.89** |
| | 70 cm | -0.88** | -0.89** |
| **PJK** | 30 cm | -0.92** | -0.82* |
| | 50 cm | -0.81* | -0.89** |
| | 70 cm | -0.83* | -0.97** |
| **RJK** | 30 cm | -0.92** | -0.92** |
| | 50 cm | -0.96** | -0.96** |
| | 70 cm | -0.43 | -0.57 |

CON, control; DJ, drop jump; LR VGRF, loading rate vertical ground reaction force; PJK, previous jumper's knee; RJK, recent jumper's knee.
*Significant at p<0.05. **Significant at p<0.01.

Figure 1 graphically represents knee flexion and the VGRF curves for the three groups.

### Vertical ground reaction force

After a significant main effect of group on LR VGRF was found ($F(2,29) = 3.02$, $p<0.05$, $n^2 = 0.17$), the post hoc test revealed a strong tendency of higher loading rates among PJK, compared with CON ($p = 0.05$). Peak VGRF was not affected by group, so no differences between groups could be detected.

### Joint kinematics

These higher LR VGRF in PJK were accompanied by a significant main effect of group on knee angular velocity ($F(2,29) = 4.6$, $p<0.01$, $n^2 = 0.44$), resulting in higher values for PJK compared with CON ($p<0.01$) and RJK ($p<0.01$). Only for the ankle flexion angle at the time of peak VGRF a significant main effect of group was found ($F(2,29) = 8.13$, $p<0.01$, $n^2 = 0.36$).

### Joint kinetics

The rate of ankle moment development showed a significant main effect of group ($F(2,29) = 4.65$, $p<0.01$, $n^2 = 0.24$), where PJK showed significantly higher values than both CON ($p<0.05$) and RJK

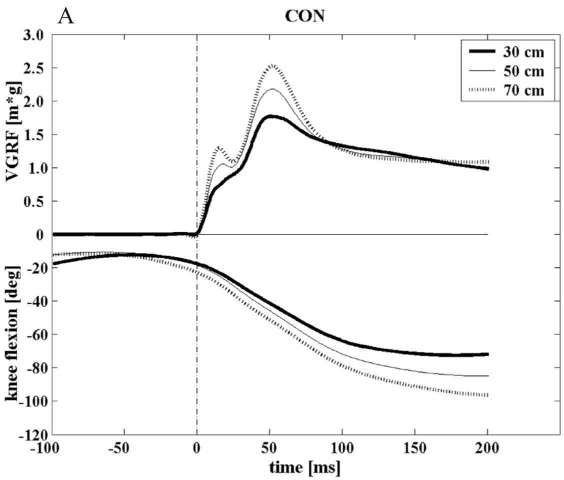
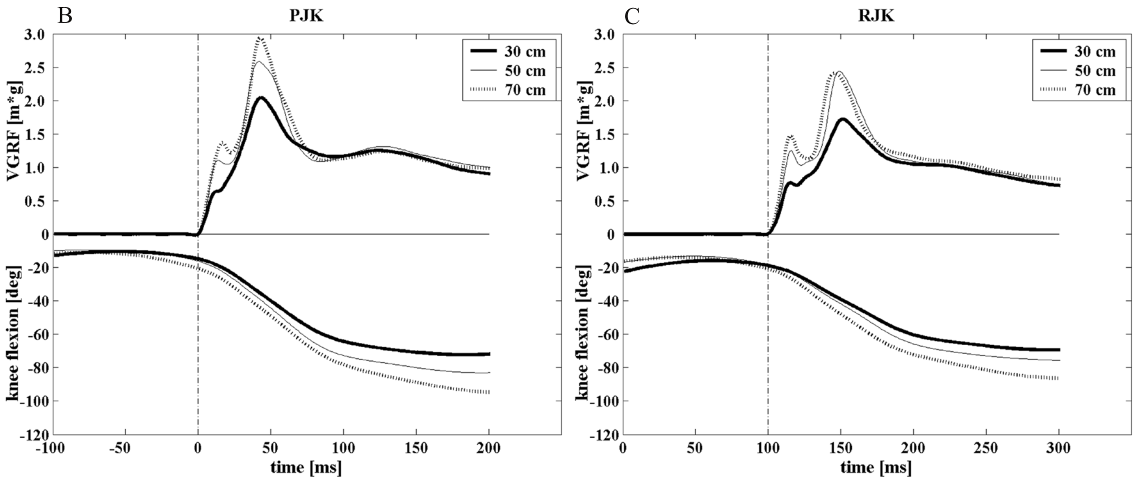



Figure 4.1. Mean vertical ground reaction force (VGRF) and knee flexion angles during landing from 30, 50 and 70 cm drop jump heights of all participants for each group (control (CON; (A)), previous jumper's knee (PJK; (B)) and recent jumper's knee (RJK; (C))). Vertical line represents moment of touch-down.
m, body mass; g, gyration.



($p<0.05$). The same pattern was seen for the rate of knee moment development, which was affected by group (F (2,29) = 3.64, $p<0.05$, $n^2 = 0.20$), where PJK showed a tendency of higher values than CON ($p = 0.08$) and significantly higher values than RJK ($p<0.05$). Peak knee moment showed a significant main effect of group (F (2,29) = 6.85, $p<0.01$, $n^2 = 0.32$), where CON showed greater knee moment values than RJK ($p<0.01$).

**Joint energetics**

Peak knee power showed a significant main effect of group (F (2,29) = 8.63, $p<0.01$, $n^2 = 0.37$), where both CON and PJK generated higher peak knee power values than RJK ($p<0.01$). For joint work, only differences in the knee joint were found. Knee joint work showed a significant main effect of group (F (2,29) = 6.44, $p<0.01$, $n^2 = 0.31$). Greater knee joint work was found for CON than for RJK ($p<0.01$).

## 4.4. Discussion

In this study, a key finding was that volleyball players with PJK seemed to land with a stiffer knee joint than CON, as appeared from significantly higher knee angular velocities, faster ankle plantar flexor moment development, and a tendency of faster knee extensor moment development and higher LR VGRF during landing (Table 4.2 and 4.3). Santello and McDonagh (1998) studied landing dynamics from different heights and found that jumping from greater heights resulted in greater peak VGRF and higher LR VGRF, whereas the ankle range of motion remained constant. This suggested an increase in leg stiffness, which was fulfilled by an accompanying increase in ankle angular velocity. Corresponding with these findings, PJK showed higher loading rates of ankle and knee moments and knee angular velocities than CON, whereas the joints' ranges of motion were the same. By performing a stiffer landing strategy, the patellar tendon, as part of the quadriceps extensor mechanism, is subjected to a higher strain. The high frequency of landing movements in volleyball and this landing strategy performed by PJK may collectively be seen as a risk factor for patellar tendinopathy. In accordance with this line of argument are the findings of Richards et al. 1996 , who already have shown a relationship between the rate of knee extensor moment development during landing from a spike jump and the presence of patellar tendinopathy.

Previous research has already demonstrated the relationship between knee flexion and landing stiffness (Devita & Skelly, 1992). Our data confirmed this finding by a negative correlation between knee flexion and LR VGRF and peak VGRF during landing (Table 4.4). In accordance with Louw et al. (2006) we measured the degree of knee flexion at the time of peak VGRF, which may be considered as more clinically relevant than the maximum knee flexion. On the basis of the suggested stiffer landing strategy by PJK, one would expect a significant main effect of group on knee flexion at the time of peak VGRF. This was not found, although a trend could be distinguished (Table 4.2). Probably the small subject numbers and the relatively high within-group variability in landing technique prevented a main effect.

The second finding of this study concerns the landing strategy performed by RJK compared with the two groups without pain at the patellar tendon region, CON and PJK. In previous research (Richards et al., 1996; Richards et al., 2002) on biomechanical risk factors for patellar tendinopathy, comparing healthy and symptomatic participants, it remained unclear whether the outcomes could be related to the development of the injury or were the result of adaptive changes in landing strategy due to the injury. The landing strategy found in players with RJK was in contrast with the landing characteristics performed by the asymptomatic PJK. RJK mainly differed significantly on biomechanical variables concerning landing stiffness by lower knee velocities, slower ankle plantar flexion and knee extensor moment development, and lower knee power values. So, the different landing strategies between the two jumper's knee groups confirm the assumption that both groups represented different populations. Compared with CON, RJK showed a landing strategy that led to lower eccentric loads, characterized by lower peak knee moment and lower knee work and knee power values (Tables 4.2 and 4.3).

The load-avoiding landing strategy performed by RJK could be interpreted as a consequence of the pain associated with patellar tendinopathy. Herewith, one should take into account that the playing level of RJK was not fully matched with the other two groups (Table 4.1) and that the RJK players theoretically might be less skilled in controlling knee flexion during landing.

Although this research was conducted with relatively small subject numbers, which influenced the effect sizes found in this study, the landing strategy performed by PJK might be interpreted as a possible risk factor and leave the player vulnerable for patellar tendinopathy. However, owing to the cross-sectional retrospective design of this study, the stiffer landing strategy performed by PJK cannot directly be attributed as a causal mechanism of patellar tendinopathy. A longitudinal prospective study with asymptomatic young volleyball players is necessary to confirm whether the landing strategy performed by PJK indeed can differentiate healthy volleyball players and volleyball players developing a jumper's knee. Our findings can be used as guidelines for which biomechanical variables could be collected. For example, instead of a full inverse dynamics approach, ambulatory body-fixed accelerometers or gyroscopes could possibly be used to gain information about joint stiffness during landing.

Volleyball trainers should be aware of stiff landing patterns among their players, and should instruct these players to soften their landings by proper ankle plantar flexion and knee flexion.

### 4.5. Conclusion

Our data comparison between volleyball players, included in CON, PJK and RJK groups, indicate that a stiffer landing strategy to accommodate impact forces might be a risk factor for the development of patellar tendinopathy. For several biomechanical variables representing knee stiffness during landing, the volleyball players with a history of patellar tendinopathy showed larger values than the controls and players with a recent patellar tendinopathy. Further research is required to validate our findings in a longitudinal prospective study among larger subject numbers and across real volleyball spike landings.

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